

EXPERIMENTAL VERIFICATION OF DYNAMIC SIMULATION

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ABSTRACT

The dynamics model here is a backhoe, which is a four degree of freedom manipulator from the dynamics standpoint. Two types of experiment are chosen that can also be simulated by a multibody dynamics simulation program. In the experiment, recorded were the configuration and force histories; that is, velocity and position, and force output and differential pressure change from the hydraulic cylinder, in the time domain.

When the experimental force history is used as driving force in the simulation model, the forward dynamics simulation produces a corresponding configuration history. Then, the experimental configuration history is used in the inverse dynamics analysis to generate a corresponding force history. Therefore, two sets of configuration and force histories--one set from experiment, and the other from the simulation that is driven forward and backward with the experimental data--are compared in the time domain. More comparisons are made in regard to the effects of initial conditions, friction and viscous damping.

INTRODUCTION

With recent developments in dynamic simulation software, there have been steady improvements in analysis and design of multibody mechanical systems. The performance of a software package has been frequently compared with that of another, but rarely with experimental data. In this research, dynamic simulation is compared with experimental data in time domain.

Through the dynamic simulation, the rigid-body (or flexible-body) equations of motion generate the positions, velocities and accelerations of the components of a given system, and the reaction forces at the system's joints. The equations of motion are usually idealized by not including Coulomb friction and viscous damping, and by simplifying actuating force elements. These idealizations manifest the limitations in the mathematical modelling of a dynamic system. There are also limitations in experimentation. The experiments provide the factual data of the actual system. But such data are not completely reliable because of errors in measurements and subsequent data analysis and interpretation.

The system chosen for the research is J.I. Case 580K backhoe. From a dynamics' standpoint, it is a manipulator of four degrees of freedom (dof) with an operator in the loop. Three dofs are controlled by hand levers for digging, scooping up, and dumping operations, and one dof by a pair of foot pedals for left and right swing motion. These four dofs are individually controlled by hydraulic cylinders that comprise a complicated circuit.

APPROACHES

The approach taken here was to divide the simulation task into multibody dynamics and control element modeling, each of which was separately validated and then later

combined together. In this paper, only the validation of the multibody dynamics is presented. The multibody dynamics includes the modeling of each component and its joints, with the assumption that applied forces or torques are supplied by the control elements. The validation will thus enable unbiased evaluation of the multibody dynamic simulation, without being influenced by the modeling technique of the controller, i.e., in this case, the hydraulic cylinders and circuitry.

The verification effort started with defining a set of static and dynamic quantities that were both measurable in the experiment and obtainable from the simulation, and that were capable of describing the system status at any specified time. Such quantities were identified as positions and velocities of the system components, and forces acting on the system's joints. In the simulation, the post-processing analysis recovered these quantities easily. In the experiment, however, each quantity demands its own transducer with signal conditioning and data analysis. As a result, experiments were carefully orchestrated with the available equipments, so that the mathematical model could simulate the same operation as in the experiment.

Although there is no established method of validating dynamic simulation in the time domain, the strategy adopted here makes use of the forward and backward (inverse) dynamic analyses, with experimentally known time histories of position and joint forces. The position history that had been measured in the experiment was input into inverse dynamic analysis, which generates a force history that would have driven the simulation model along the input position history. Under the ideal condition such that the dynamic simulation describes the exactly same behavior of the actual system, the two force histories — one from the experiment, the other from the inverse dynamic analysis — should be the same. But, in reality, there inevitably exists a discrepancy between these two. This discrepancy is viewed as a measure of the validation. Similarly, the force history that had been obtained in the experiment was fed into forward dynamic analysis, which generates position history that would have been exactly the same as measured under the ideal condition. Again this position history was compared with the experimental position history.

EXPERIMENTS

Since the boom carries most of the load, its static and dynamic stress analysis is the major concern in design and analysis. Once the dynamic model is validated, it should generate reliable joint reaction forces for dynamics and stress analysis. The experimental effort was thus concentrated on the boom and its hydraulic cylinder. The transducers were attached to boom are a load cell that measures the boom cylinder force output, a differential pressure transducer between the supply and drain sides of the boom cylinder, and a position/velocity transducer for the boom cylinder piston movement. The experiments were conducted by actuating the boom cylinder with various fixed configurations of the dipper and bucket assembly. Among those various configurations, two of them were selected for experimentation and simulation. First, the bucket and the dipper were tucked in under the boom, as shown in Fig. 1. Second, the bucket and the dipper were stretched out, as shown in Fig.3 .

Experimental data were digitized, inspected, and recorded in the IBM PC/AT at the experimental site. Later in the lab, the PC was connected to the local network to unload the data to an Apollo workstation. The data were then retrieved, filtered, interpreted, and supplied for comparisons of experimental with theoretical results in static stress analysis and dynamic behavior, and verification of hydraulic actuator models.

Two types of experimental data are used in the dynamic simulations: force and relative displacement histories of the boom cylinder for the forward and backward simulation. Both quantities were measured while the backhoe was being operated through a predefined trajectory. The relative displacement was measured by a position transducer

with one end attached to the piston and the other end to the cylinder housing. The cylinder force was measured by a load cell placed at the piston end of the cylinder.

Experiment I

In the first experiment, the backhoe is in folded-up configuration; that is, the dipper and bucket cylinders are fully extended, so the dipper and bucket are tucked in under the boom. The angle between the boom and the dipper is about 42 degrees. The only degree of freedom allowed is the rotation around the revolute joint between the boom and the swing tower. At the beginning of an experiment, the boom was in upright position, making an angle of 4 degrees with the vertical (Fig. 1). The boom was slowly lowered from the upright position until it reached 38 degrees of boom angle, then stood still a few seconds, and was brought back up to the original position. The duration of this operation was about 30 seconds.

A typical relative cylinder displacement history measured by the position transducer is shown in Fig. 2. Since the boom cylinder extends while the boom drops downward, the rising trend of the displacement history should be interpreted as the downward motion of the boom.

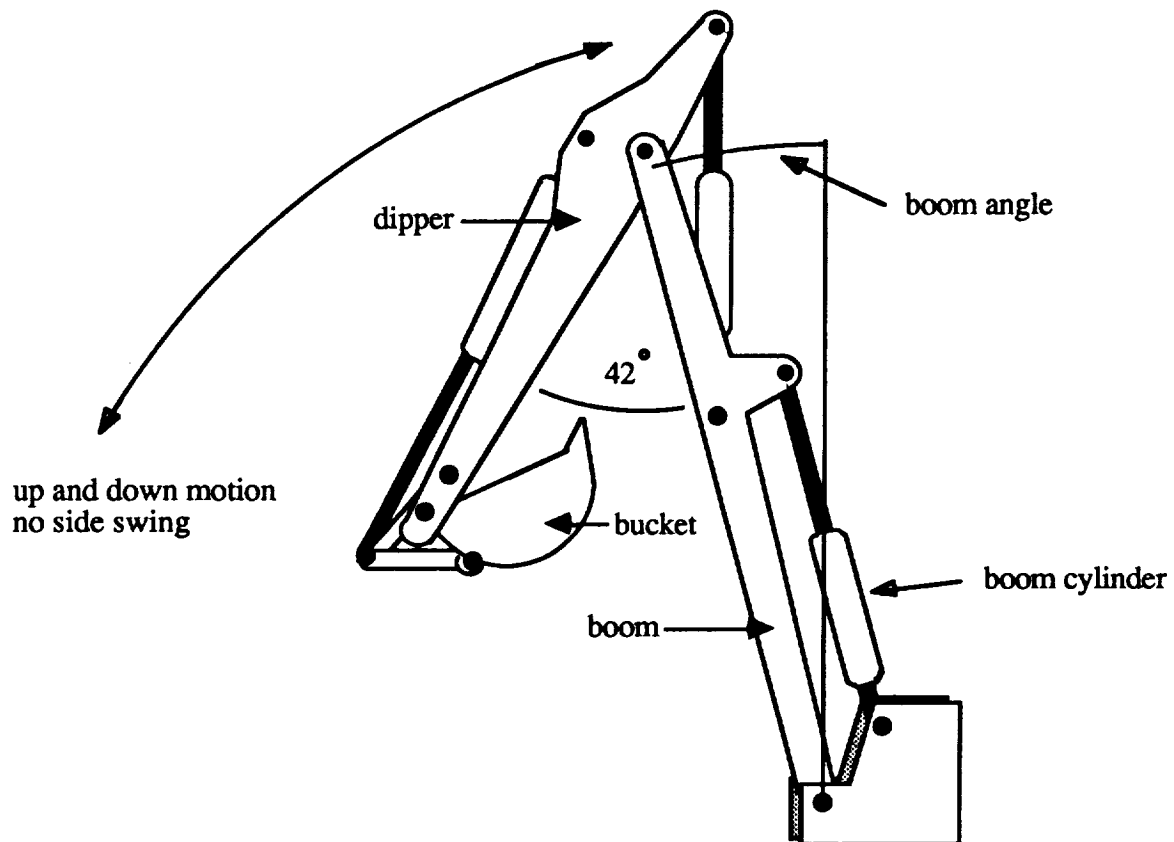
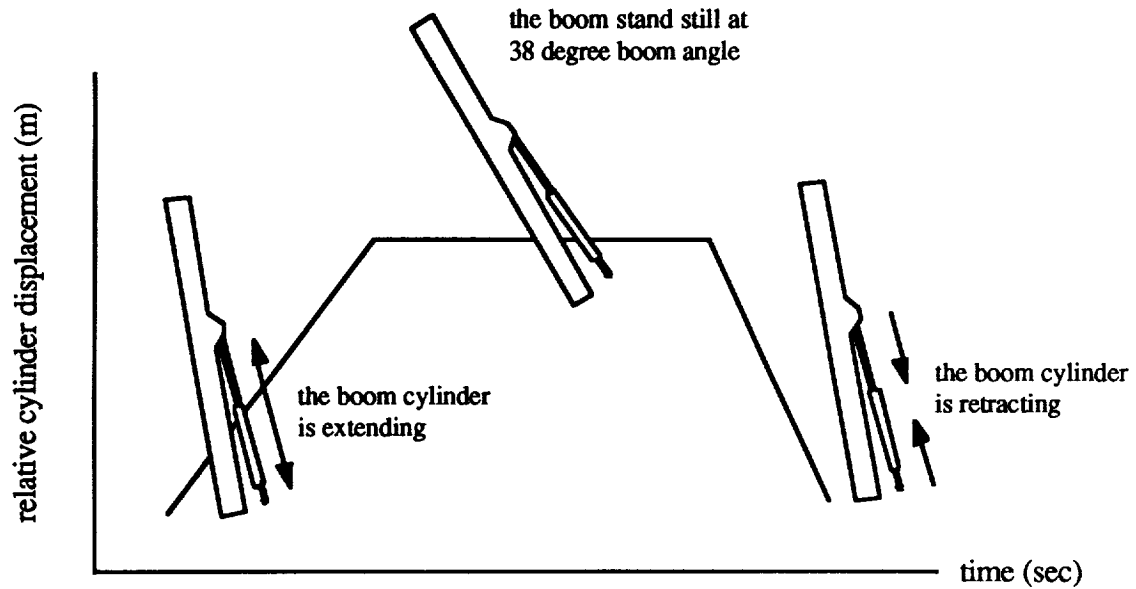


Figure 1 Configuration of experiment I



The motion of the backhoe can be divided into three stages

Figure 2 Position history of experiment I

Experiment II

In the second experiment, the dipper and bucket cylinders were fully retracted so that the backhoe stretched out to its longest reach (Fig. 3). The bucket initially rested on the ground. The boom slowly lifted the bucket up until the bucket reached about 2 m above the ground. Then it brought the bucket back to its original position. This time the whole operation took about 8 seconds. Figure 4 shows a typical relative cylinder displacement history measured in experiment II.

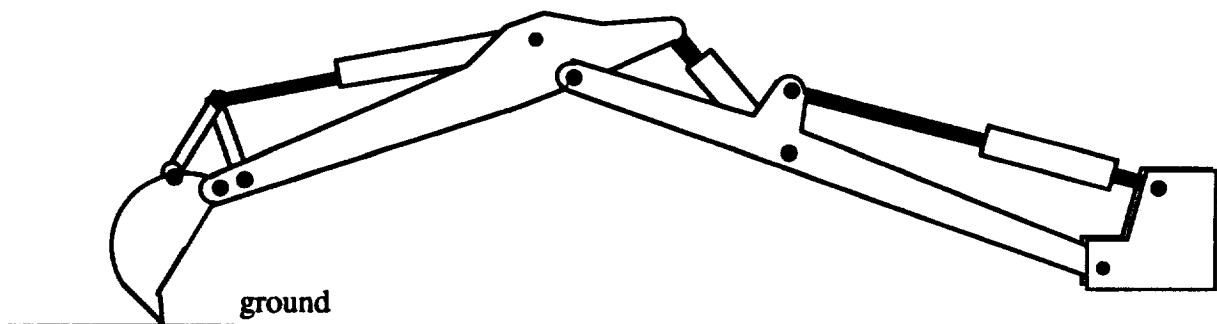


Figure 3 Initial configuration of backhoe in experiment II

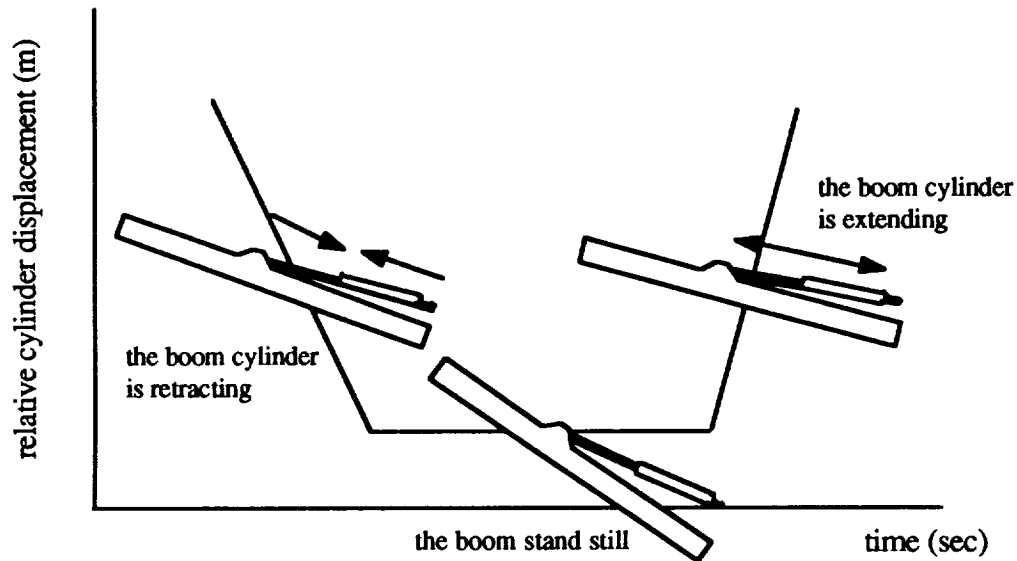


Figure 4 Position history of experiment II

DYNAMIC SIMULATION

Modelling

The dynamic modelling of the backhoe started with a relatively simple model including only the major components, and then added more components such as pins until every single component was accounted for. Table 1 lists the major components and the types of joint used in the model (also see Fig. 6). One of the most significant changes made in model refinements is the addition of the weights of pins and hydraulic fluid. These masses have been regarded insignificant until we found that the simulation model was lacking in the total inertia.

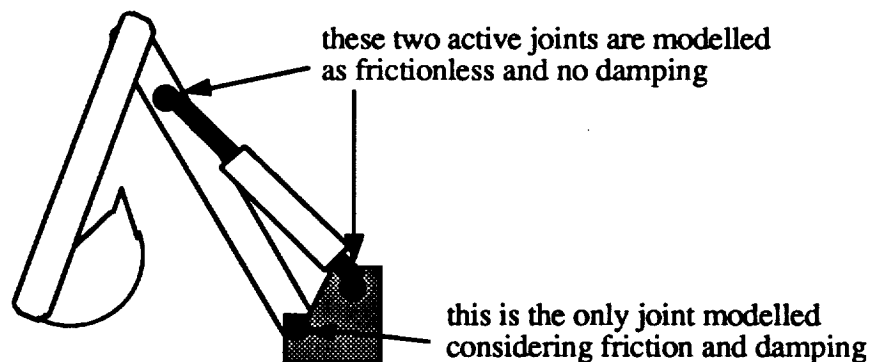


Figure 5 Active joints of backhoe

Among the joints, three of them are active during the experimentation, the locations of these active joints are shown in Fig. 5. There evidently exist viscous and Coulomb friction damping forces at these joints. Since the revolute joint between the tower and the boom is the biggest joint among them, the complexity of the analysis is reduced by modelling that joint as the only joint with viscous and friction damping.

Table 1 Bodies and Joint Types

Body name	Joint Type	Body 1	Body 2
Boom	revolute	Tower	Boom
Dipper	revolute	Boom	Dipper
Bucket	revolute	Dipper	Bucket
Coupler I of bucket	revolute	Coupler I	Coupler II
Coupler II of bucket	cylindrical	Bucket	Coupler II
Boom cylinder	cylindrical	Boom cylinder	Tower
Boom piston	cylindrical	Dipper cylinder	boom
Dipper cylinder	cylindrical	Bucket cylinder	Dipper
Dipper piston	spherical	Dipper	Coupler I
Bucket cylinder	spherical	Boom Piston	Boom
Bucket piston	spherical	Dipper Piston	Dipper
	spherical	Bucket piston	Coupler I

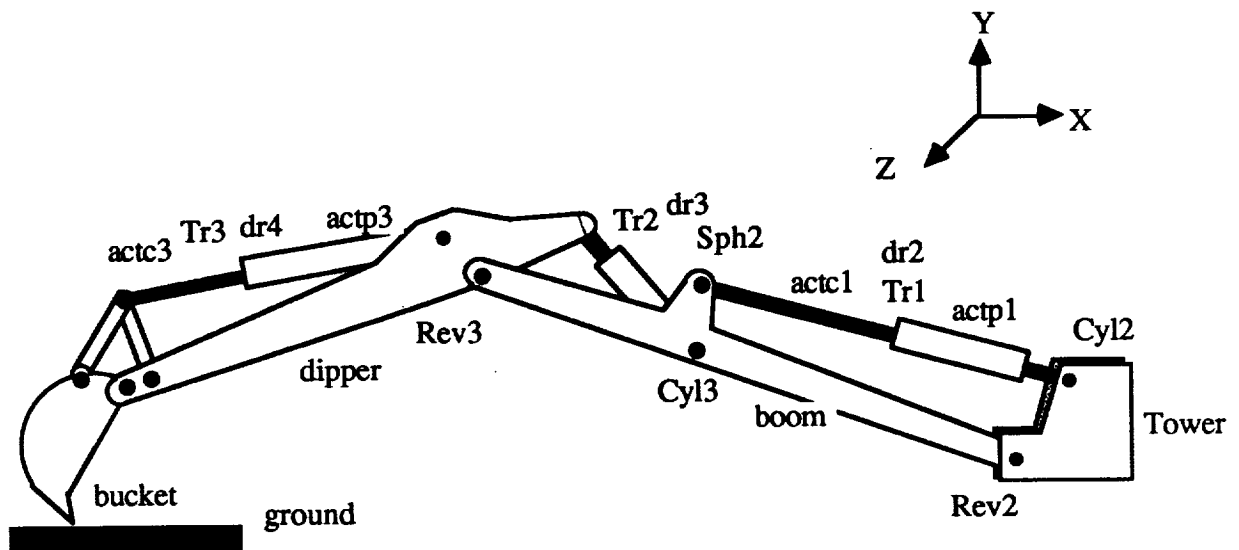


Figure 6 Joint Definition

Initial configurations

In the time-domain validation, the initial conditions of the simulation must first and foremost equal those of the experiment. This requires static equilibrium analysis in the simulation and accurate measurements of position and reaction forces in the experiment. In fact, some initial configurations had to be excluded on the grounds that they were statically indeterminate.

At the beginning of experiment I when the system is in static equilibrium, the force measured at that moment was used to calculate the exact initial position of the backhoe in the experiment. The position measurements were also available from the experiment, but were much less accurate than the force measurement, because a little error in position measurement resulted in a huge error in the corresponding equilibrium force at the initial configuration, which was almost vertical.

In experiment II, a different approach was taken to determine the initial configuration. Since the initial position of the tip of bucket was precisely known, the initial configuration was determined by using this fact. The mass center of the swing tower is defined as the reference coordinate center of a simulation, so the vertical distance from

the reference center to the ground has to be measured. This distance was measured to be about 0.8m. The initial configuration of experiment II is thus obtained based this information and the kinematic relations between bodies of the backhoe model.

SIMULATION AND COMPARISON

In comparison with experiment I, several viscous damping ratios have been tested in the dynamic simulations. Figure 7 shows force comparison in which viscous damping does not play a significant role. Indeed, it was a slow operation, so the viscous damping force was expected to be small. However, the effect of viscous damping is pronouncedly exhibited in the displacement comparison. In Fig. 8, the viscous damping coefficients of 10 and 15 (kN/m/sec) make the simulation close to the experimental data.

In Fig. 9, the simulation with the viscous damping coefficient of 15 (kN/m/sec) continues to move upward (actual motion downward) even when the actual system stopped and stood still, thus exposing the absence of Coulomb friction in the simulation model. The existence of Coulomb friction is also observed in Fig. 7. The force from the simulation is not reduced by the amount of Coulomb friction force, whereas the applied force has already reflected loss from Coulomb friction. Therefore, the simulation force would be equal to the sum of the Coulomb friction and applied forces if the simulation exactly matched with the experiment. In the first half where the friction force is in the same direction with the applied force, the simulation force appears above the actual applied force. In the second half where the friction force is in the opposite direction to the applied force, the simulation force appears below the actual applied force.

In experiment II, the long stretch of the backhoe in combination with a faster maneuver induced vibrations that are visible in Fig. 10. But the simulation shows no vibration but follows the general trend, because the system is modelled with rigid body dynamics. Figure 11 shows a good agreement between the simulation and experiment in position history.

DISCUSSION

When the experimental position history was input to inverse dynamic analysis, it was differentiated twice to obtain velocity and acceleration. Along with this digitized position history, however, noises and discontinuities were also differentiated twice, thereby creating quite a few "jerks", which in turn made the simulation force fluctuate spuriously. To correct this problem, three smooth curves of first and third order polynomials were pieced together to approximate the experimental position history. At the two junction points, spurious peaks are still observed in Fig. 7 and 10.

Experimental estimation of viscous and Coulomb friction damping should accompany the analytical effort in which several dynamic simulations were performed with different damping coefficients. These damping forces were not so significant in Fig. 7. But their effect on the displacement is quite noticeable as shown in Fig. 8.

The validation in the time domain requires that the initial condition of the simulation should equal that of the experiment. This requirement is most of times very difficult to satisfy, because it involves static equilibrium analysis in the simulation and accurate measurements of position and reaction forces in the experiment.

FIG. 7 EXPERIMENT I: FORCE COMPARISON

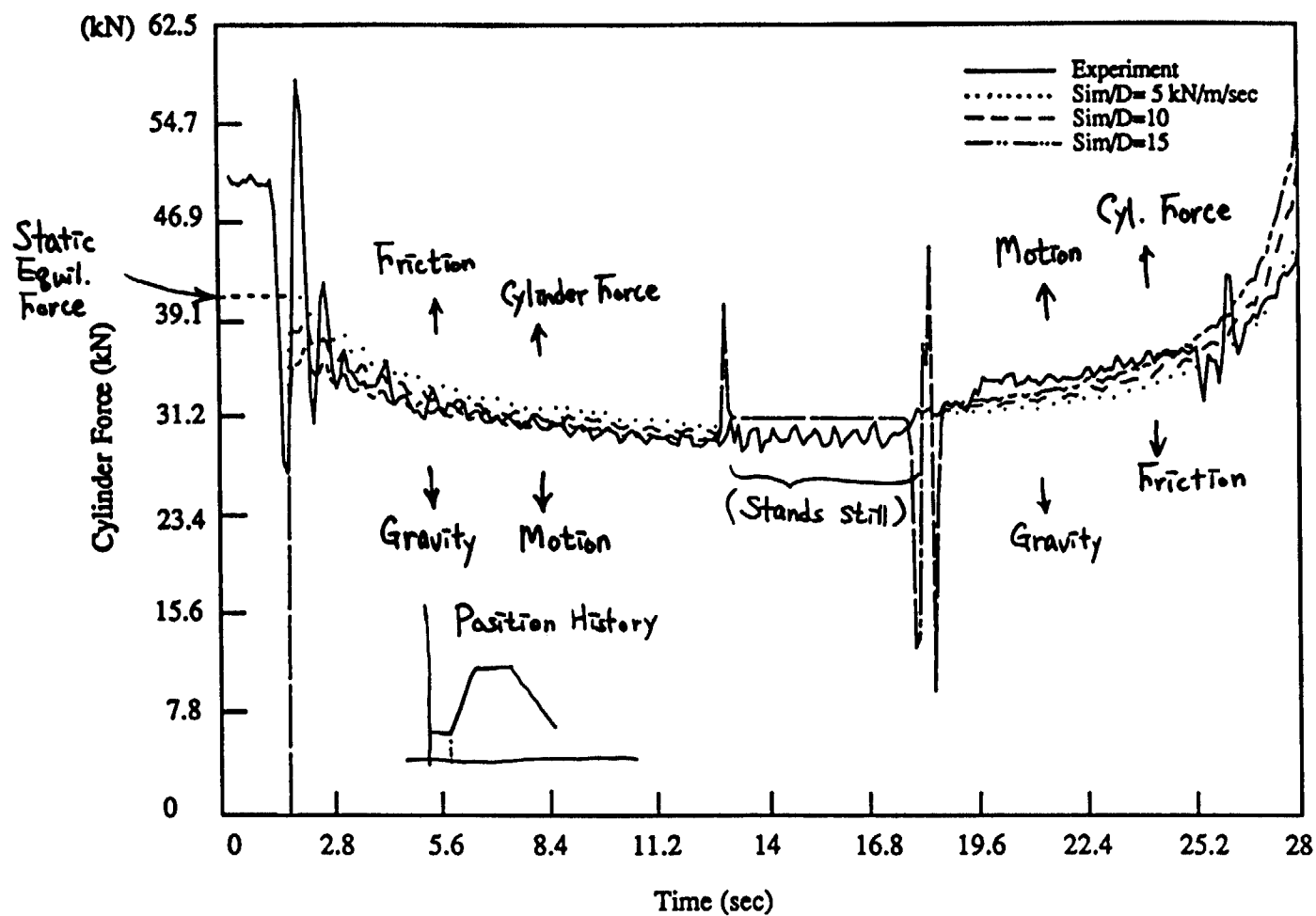


FIG. 8 EXPERIMENT I: POSITION COMPARISON

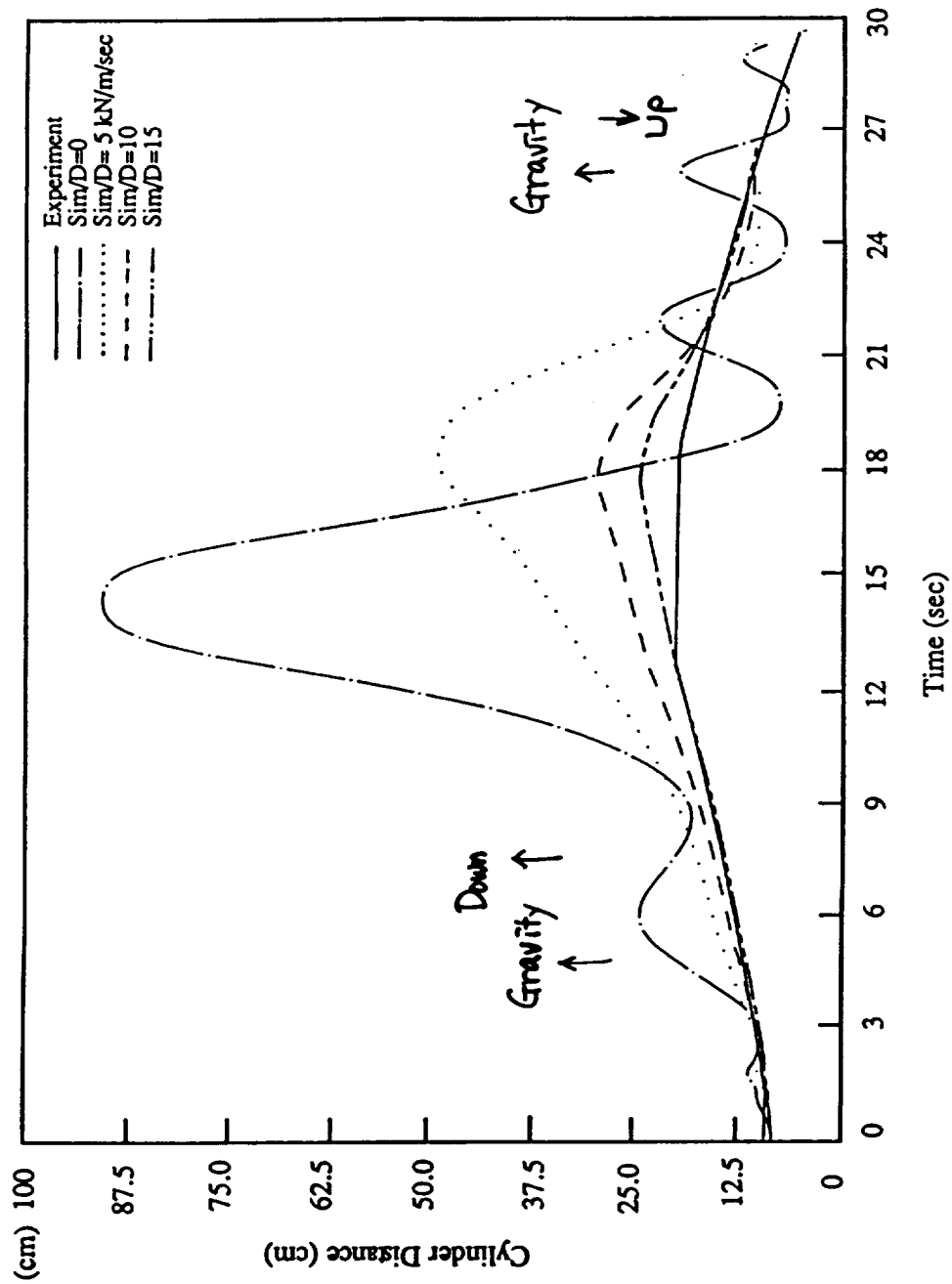


FIG. 9 EXPERIMENT I: POSITION COMPARISON

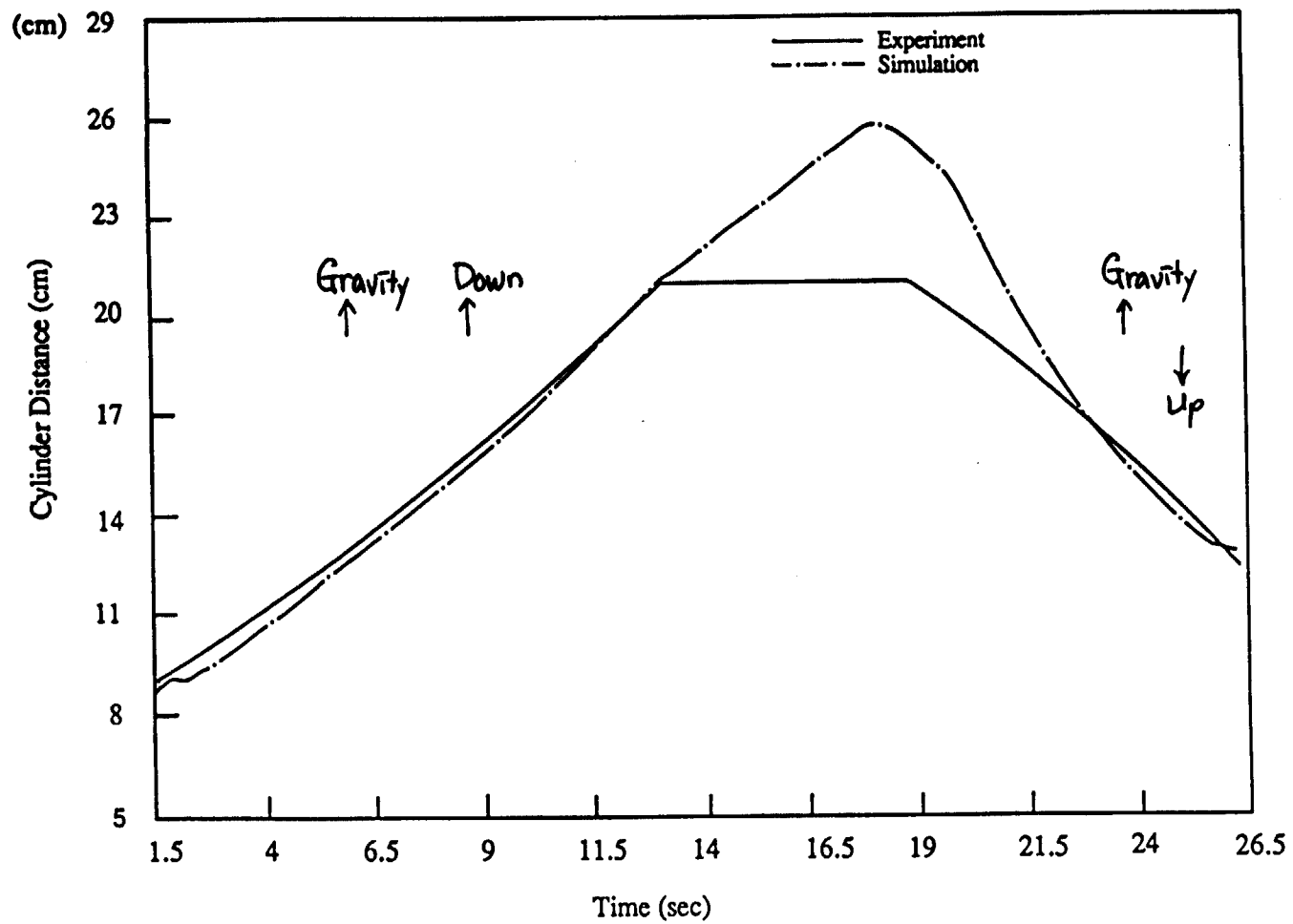


FIG. 10 EXPERIMENT II: FORCE COMPARISON

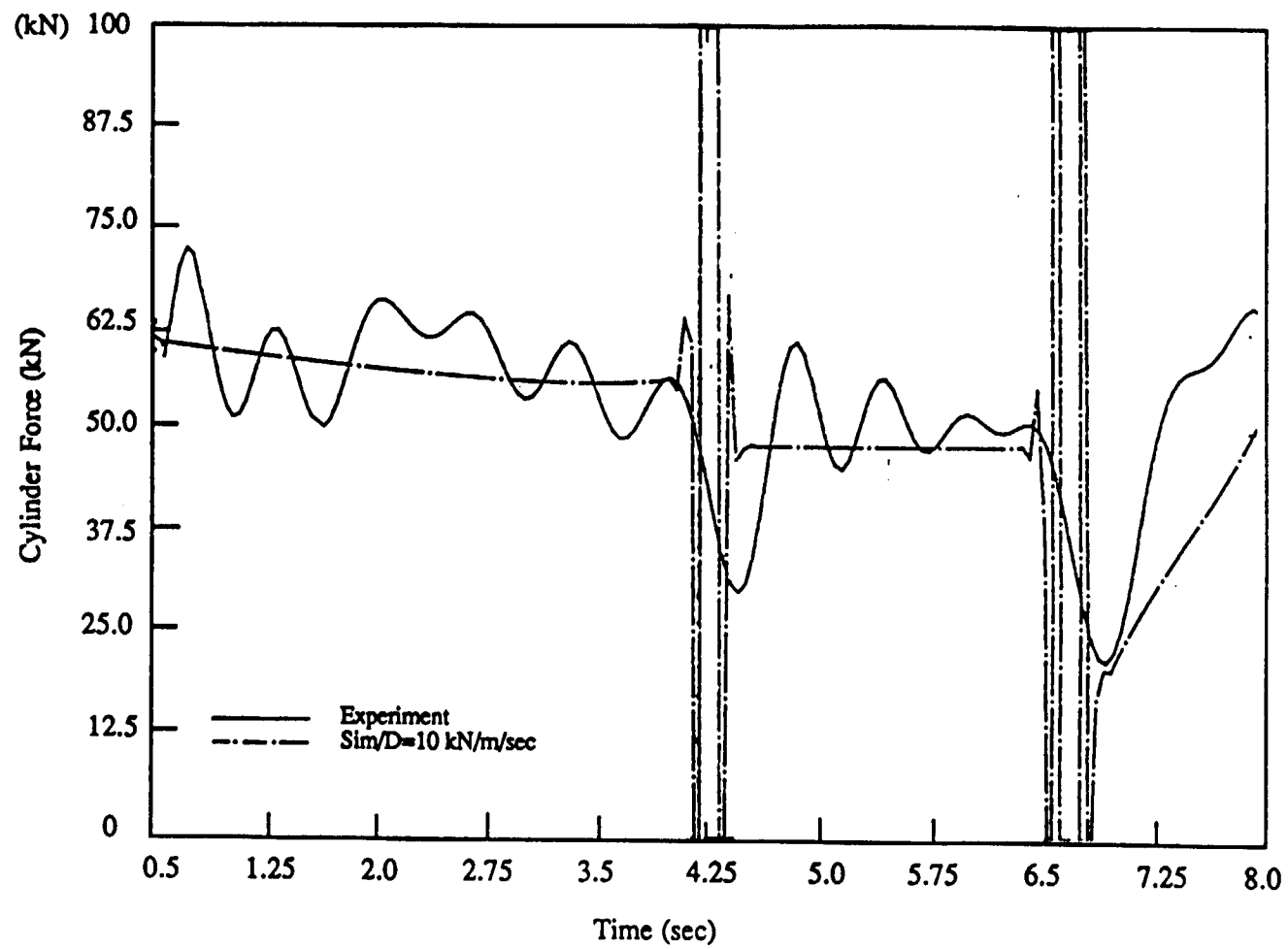


FIG. 11 EXPERIMENT II: POSITION COMPARISON

